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Body temperature and heat exchange during treadmill running in dogs[1]

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YOUNG, D. R., R. MOSHER, P. ERVE AND H. SPECTOR. *Body temperature and heat exchange during treadmill running in dogs.* J. Appl. Physiol. 14(5): 839–843. 1959.—Body temperature during treadmill running was studied in six dogs at seven different grades from 0–22 degrees of inclination. The replicate variability in the work rectal, skin and fur temperature was ±0.5°F, ±1.4°F and ±1.3°F, respectively. At grades up to 12 degrees of inclination there is a prolonged steady state in the rectal temperature. At higher grades there is a progressive increase in rectal temperature with running time. Body surface temperatures show little affect at the lower grades. At higher work intensities there is an increase in skin and fur temperature. Maximum heat storage varied from 21.3–41.3 Cal. during short term exhaustive work. This type of calculation is discussed critically. The relationship between rate of rise in rectal temperature and maximum performance time was studied. Without regard to work load a product-moment correlation coefficient of +0.991 was found.

WHILE STUDIES by Dill *et al.* and Rice and Steinhaus reported in 1931–33 (1–3) indicate a general agreement that elevated body temperature is a major factor limiting the ability of dogs to perform hard physical work, data on the effect of work load on maximum body temperatures attained, reliability of temperature measurements, and the mechanisms involved in heat loss in the working dog are not available.

Studies in our laboratory have been directed towards *a*) analyzing the factors which regulate body temperature in the dog during controlled levels of work output and *b*) determining the relationship between body temperature and performance capacity. Since quantitative studies in temperature regulation necessarily require estimates of thermal balance, some attention has been focused on heat exchange employing the principles of partitional calorimetry.

The studies presented here provide information of importance for the practical applicability of treadmill tests and for interpretation of physiological responses to exertion in the dog.

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METHODS

The experimental animals were six healthy, pure-bred, male beagle dogs which had been in weight equilibrium for 2 months prior to testing and had the following characteristics: age, 11 months; weight, 8.8–12.5 kg; height, 30.5–35.6 cm. At the time of measurement all dogs were in a high state of physical conditioning.

Performance was measured during work of graded intensity on the motor-driven treadmill. All tests were performed at a speed of 3.63 mph. The treadmill was equipped with an electric grid, mounted at the rear of the machine, which maintained motivation to run at a high level. Periodic wetting of the hindquarters of the animals served to increase the aversion to the stimulator and insured maximum performance. The environmental conditions were as follows: dry bulb temperature, 76° ± 1.5°F; relative humidity, 53 ± 3%; lighting, noise level and air movement held constant. Neglecting eddy currents, the mean air velocity was 35.5 cm/sec.

Continuous measurements of rectal (T_r), skin (T_s) and fur (T_f) temperature were made, utilizing thermistor probes with flexible leads indicating through a multichannel Tele-thermometer (Yellow Springs Instrument Co.). Rectal temperature was obtained from a thermistor inserted 6 inches into the rectum; skin temperature was measured utilizing a surface temperature probe (3/8-in. diam.) placed on a shaven area of the chest behind the right front leg, midway between the ventral and dorsal line. Fur temperature was obtained from a surface probe placed directly on the fur on the left side of the chest. Both surface probes were held in position with an elastic strap fastened about the chest of the animal.

Respiratory gas exchange was determined by collection of expired air in chain-compensated gasometers. The especially constructed respiratory masks contained internal inspiratory and expiratory valves and were designed to permit minimum discomfort and maximum ventilation during the heavy work loads. A thermistor inserted directly into the mask measured expired air temperature. For collection of work gas samples the dogs wore the mask for only 2.5 minutes, 1.5 minutes for adjustment to the mask and flushing of the gasometer and 1 minute for sampling. The dogs were trained to accept the mask without breaking stride.

O_2 uptake and CO_2 production were measured by analysis of the expired air in a Beckman O_2 analyzer and a Haldane apparatus, respectively.

In the principal tests, samples of expired air were collected twice during a 40-minute period of work, at 20 minutes and 40 minutes from the start of running. However, during the short-term, exhausting work situations, samples were collected at 5, 10, 15 and 20 minutes from the start of running.

Calculations of caloric expenditure were made from the tables of Zuntz as provided by Best and Taylor (4). No corrections were made for protein metabolism. In computing respiratory gas exchange and in subsequent estimates of heat loss no need was found to correct for differences between inspiratory and expiratory volumes.

Heat loss during work was determined from the change in the mean body temperature, ΔT_m (5) by the relationship heat loss = 'waste heat' of muscular effort $- W \times 0.83\ \Delta T_m$, where W is the body weight in kilograms and 0.83 the specific heat of tissue in Cal/kg. The waste heat of muscular work was computed from the net efficiency of grade running (6), wherein waste heat production = total heat production − caloric equivalent of physical work. Heat storage, $W \times 0.83\ \Delta T_m$, is obtained from the excess waste heat production minus the heat loss.

A relatively independent estimate of heat loss was calculated from the respiratory heat loss and loss through radiation and convection. In computing these values the following sources of error have been considered:

1) Despite standardization in the placement of the surface probes some error in temperature measurement is expected from variations in the external pressure on the probes. Since preliminary tests showed that skin and fur temperatures were substantially similar at various locations on the chest and abdomen, it is assumed that the measures taken reflect the mean overall body surface temperature.

2) Convective heat loss was determined from the following relationship, $C = K_c \sqrt{V}(T_f - T_a)$ where C is the heat loss, K_c is a constant, V is the velocity of air in centimeters per second and T_f and T_a are fur temperature and room temperature, respectively, in centigrade degrees. While it is recognized that K_c may vary somewhat with the individual (7), a constant value of 2.0 Cal/m²/hr/°C was used in the calculations.

3) Radiative heat interchange was determined from the Stefan-Boltzmann equation $R = A_r K_r (T_f^4 - T_a^4)$, where A_r is the effective radiation surface of the body in square meters, K_r is the universal radiation constant (4.92×10^{-8} Cal/m²/hr.) and T_f and T_a are the temperatures of the fur and room air, respectively, in absolute degrees. During work, the total body surface area ($11.2W^{0.667}$) is a good approximation of the effective radiating surface. Ambient air temperature provides a reasonably accurate measure of the mean radiant temperature of the environment.

4) Respiratory heat transfer was determined from three factors, *a*) the evaporative water loss, *b*) heat loss through warming inspired air and *c*) the 'drip' loss, i.e. the heat abstracted from the body by the excess fluid draining from the oral surfaces. The latent heat of vaporization of water at the observed work body temperatures has been estimated to be 0.574 Cal/gm (8), while the water content of saturated expired air at 84°F has been estimated to be approximately 0.036

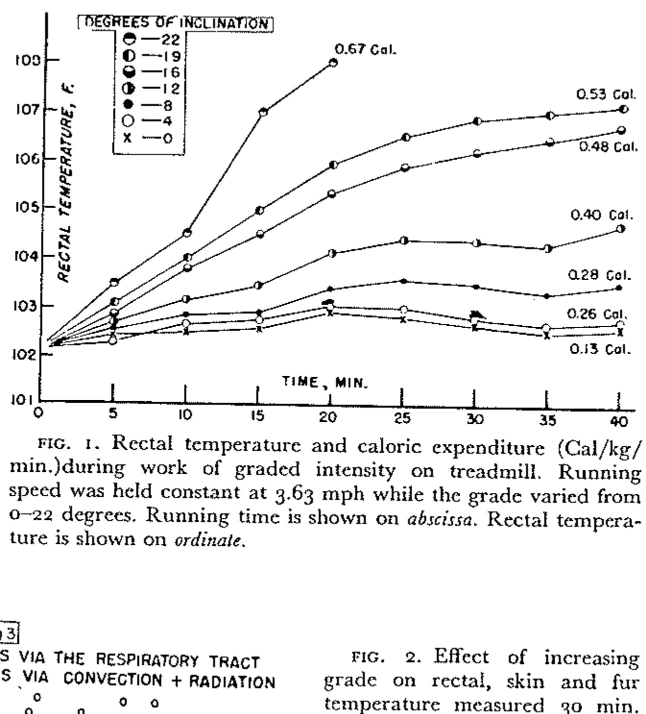
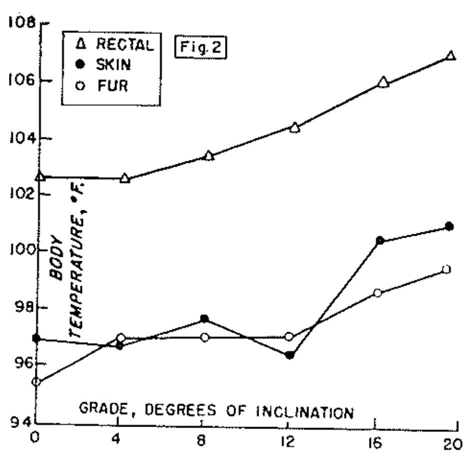


FIG. 1. Rectal temperature and caloric expenditure (Cal/kg/min.) during work of graded intensity on treadmill. Running speed was held constant at 3.63 mph while the grade varied from 0–22 degrees. Running time is shown on *abscissa*. Rectal temperature is shown on *ordinate*.



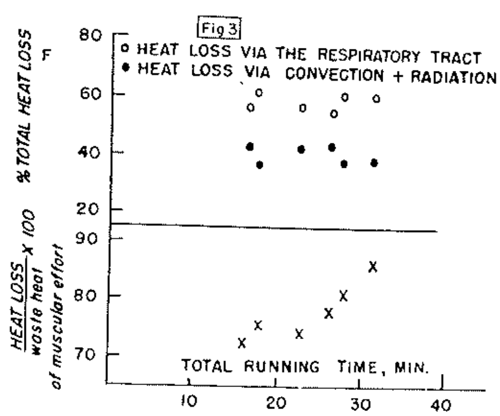


FIG. 2. Effect of increasing grade on rectal, skin and fur temperature measured 30 min. after start of running. Running speed was held constant at 3.63 mph. Grade varied from 0 to 19 degrees of inclination.

FIG. 3. Relationship between heat loss and exhaustive running time (3.63 mph at 22 degrees). Total running time is shown on *abscissa*. Percentage of heat loss is shown on *ordinate*.

gm/l. (9, 10). The heat required to warm inspired air without a change in volume was calculated to be 0.00025 Cal/l/°C. Drip loss was determined by the difference between total weight loss during work and the water content of the expired air. The heat content of water lost via this channel was taken as 0.040 Cal/gm (11).

Computation of heat transfer via the respiratory tract, convection and radiation has been based on mean respiratory volumes and body temperatures measured during a short-term work situation.

RESULTS

Effect of increasing grade. The effect of seven different grades on the body temperature was studied in six dogs. A systematic study of gas exchange and caloric expenditure during work has been presented in the preceding paper (12).

Figure 1 shows the increase in rectal temperature and mean caloric expenditure at the seven different grades used. At grades of 0–12 degrees of inclination the dogs were able to maintain a steady-state temperature with, however, a moderate degree of heat storage. At grades in excess of 12 degrees, body temperature shows a continuous rise with running time.

It will be noted in figure 2 that, while the work rectal temperature shows almost a linear increase with grade, skin and fur temperatures show only minor variations up to a grade of 12 degrees; thereafter, the skin and fur temperatures increase markedly. Thus, at the lower grades there is little transfer of heat from the core to the body surface by way of tissue conductance and convective transfer through increased blood flow to the skin. Consequently, at low work intensities heat loss is principally achieved through the respiratory tract. At the higher work loads additional heat exchange via radiation and convection is promoted by the elevated body surface temperature.

At 19 degrees of inclination the skin temperature and fur temperature are 101°F and 99.5°F, respectively. The 1.5°F difference in temperature reflects the insulative properties of the fur.

Variability in body temperature. Determination of net heat exchange is dependent on the reliability of temperature measurements. We have examined the variability in rectal, skin and fur temperature in replicate work tests.

Table 1 summarizes the variability observed in the 40-minute work (3.63 mph at 16 degrees of inclination) body temperatures. The standard deviations are ±0.5°F, ±1.4°F and ±1.3°F for the rectal, skin and fur temperature, respectively, during work. Since tests showed that these errors of measurement do not vary with the work situation, they may be taken as constant errors of individual measurements.

The lowest variability is observed in the rectal temperature. The higher variability shown by the skin and fur temperatures is probably due in part to variations in the positioning of the surface probes as well as to variations in skin blood flow.

TABLE 1. *Variability in Rectal, Skin and Fur Temperatures at Rest and During Running on the Treadmill**

	Rectal	Skin	Fur
Resting temp., °F	102.1 ± 0.4†	94.8 ± 1.7	94.0 ± 1.1
‡Final work temp., °F	105.9 ± 0.5	98.9 ± 1.4	97.9 ± 1.3

* Measured at a speed of 3.63 mph and 16 degrees of inclination. † S.D. (dogs × trials) based on 8 degrees of freedom. ‡ Measured 40 min. after start of running.

TABLE 2. *Total Heat Loss During Short-Term Exhaustive Work (3.63 mph at 22°)*

Dog No.	Heat Loss in Calories	
	Estimated from ΔT_m	Estimated from respiratory, convective and radiative losses
22	139.1	135.5
23	87.3	80.8
33	129.6	133.2
34	128.4	128.4
35	83.3	85.6
40	99.8	102.3

To evaluate the reliability of results, the relationship between the changes produced by the controlled independent variables and variations due to uncontrolled factors is of importance. The random variability in fur temperature after 40 minutes of work is 1.3% of the mean. The average increase in fur temperature due to work is 4.1%. Thus, the variations in fur temperature due to the factor of work are approximately three times (3.1 × S.D.) larger than the variations due to uncontrollable factors. Therefore, it is probable that the surface temperature reflects a true response to work.

Heat exchange during work. Heat loss during an exhausting work task (3.63 mph at 22 degrees of inclination) was estimated as described above. It can be seen in table 2 that there is good agreement in estimated heat loss as determined by two relatively independent methods. Maximum heat loss varied from 83.3 Cal. to 139.1 Cal. for the six dogs.

Heat loss was plotted against exhaustive running time. These data are presented in figure 3. For all dogs, 59.4% of the heat lost is dissipated through the respiratory tract and 40.6% via convection and radiation. The relationship is constant for all performance times. On the other hand, the data suggest a relationship between performance capacity and ability to dissipate heat. Thus, the dog showing the shortest running time eliminated only 72% of the total waste heat of muscular effort, while the longest runner dissipated 85% of the excess heat. Heat storage in these dogs varied from 21.4 Cal. to 41.3 Cal. and showed no systematic relationship with maximum running time. The values set forth here suggest that performance is more dependent on ability to lose heat than on heat storage, per se.

Performance as related to body temperature. That performance is dependent on the body temperature was demonstrated in 28 all-out endurance tests. The treadmill speed was held constant at 3.63 mph for all tests, whereas the grade varied from 15–22 degrees to induce short- as well as long-term exhausting runs. Performance varied from 15.7 min–167 min. The criteria selected were exhaustion as evidenced by inability of the animals to continue running and the time during the run required to attain a rectal temperature of 106.0°F. Selection of this particular body temperature was based on earlier observations of maximum work rectal temperatures of 107.0°F–110.1°F in 18 dogs. Thus in the dogs studied, a temperature of 106°F is one which can be attained by all animals. Moreover, it is apparent in figure 4 that the time required to attain this temperature during an exhaustive run distinguishes animals within a well-trained population, the poorer performers showing characteristically a more rapid rise in body temperature.

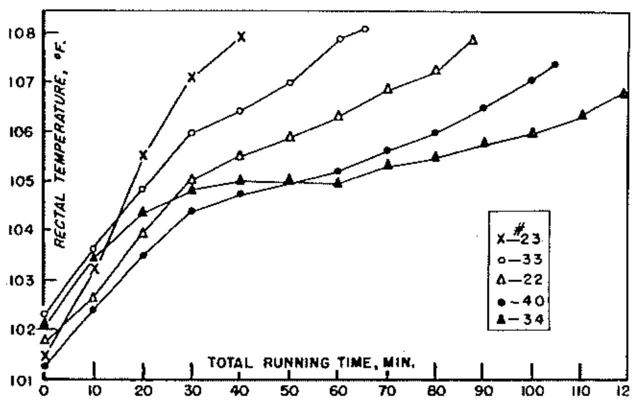


FIG. 4. Individual variations in rectal temperature during an exhaustive running test (3.63 mph at 17 degrees).

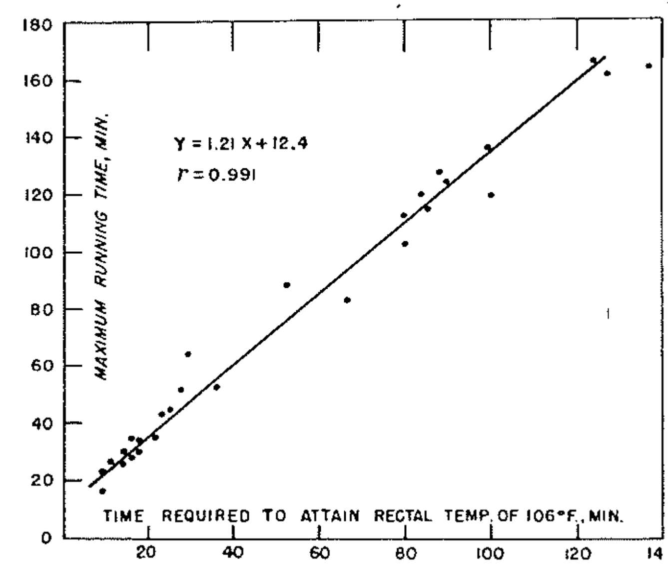


FIG. 5. Relationship between rise in rectal temperature and maximum running time in treadmill tests of graded intensity. Time required to attain a rectal temperature of 106°F during exhaustive running is shown on *abscissa*. Maximum running time is shown on *ordinate*.

Figure 5 shows the relationship between the time required to attain a rectal temperature of 106°F and maximum performance capacity. The product-moment correlation coefficient for these two functions is +0.991. The authors are aware of the theoretical limitations in drawing this correlation due to the unusual grouping of the data. A linear relationship of the form $y = ax + b$ was fitted to the data by the least squares method, where y is the total running time in minutes, x is the time required to attain a rectal temperature of 106°F and a and b are constants.

A high degree of dependence of running ability on the rate of increase in rectal temperature ($r + 0.991$) was found, yet no relationship between performance capacity and heat storage was evident. It is believed that the effect of temperature on the body is a complex phenomenon wherein the ability of tissues and organ systems to tolerate heat may in part determine the capacity to perform hard work. It is probable that individual variations exist in ability to maintain functional performance at a high body temperature. Further tests are needed to isolate and identify the critical heat-sensitive components of the body.

DISCUSSION

Effect of body temperature is an important aspect in treadmill running in the dog. The data presented indicate that there was body heat storage at all grades tested. The small intrinsic variations in rectal temperature imply good reproducibility. Comparatively small variations in grade produce measurable differences in rectal temperature. At grades up to 12 degrees there is a prolonged steady state maintained with minor variations. Higher work intensities (in excess of 0.40 Cal/kg/min.) result in a sustained rise in the rectal temperature.

At the lower grades, heat loss by convection and radiation is constant. During heavier work, elevated body surface temperatures promote increased heat flow through these channels. It is not known to what extent the increased skin temperature observed at the heavy work loads is due to increased blood flow.

In a hard work situation approximately 60% of the heat loss occurs via the respiratory tract. This factor includes heat loss through warming inspired air, the latent heat of vaporization of water and the heat lost with moisture draining from the oral surfaces. Forty per cent of the heat is lost by radiation and convection.

It has been shown that ability to regulate body temperature is of prime importance in maintaining a sustained work effort. Although there is a high degree of correlation between rate of rise in rectal temperature and performance capacity, the specific influence of high body temperatures on performance is not clear. If temperature limits performance through a direct effect on the body, one would anticipate that running time would be related to the quantity of heat stored within the body. The results fail to show this systematic relationship.

Accordingly, a hypothesis may be suggested wherein at high body temperatures a large portion of the cardiac output is diverted to the skin for cooling purposes, thus resulting in a reduced blood flow to the central nervous system and other critical areas. If this is true, then deterioration in ability to perform hard work in the dog is due to the same factors which limit performance in man in a hot environment.

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